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THE ANGULAR DISTRIBUTION OF CHARACTERISTIC DIFFUSE LIGHT IN NATURAL WATERS*

BY

LESTER V. WHITNEY

*State Teachers College
Springfield, Missouri

INTRODUCTION

Several investigators have conducted experiments on the angular distribution of light in natural waters (1, 2). It has been found that the direction of maximum light intensity from the sun moves toward the vertical with increase in depth. It has also been found that light becomes more diffuse but remains highly directional with increase in depth. Clarke has pointed out the biological importance of the directional properties of deep water illumination (3). The purpose of this article is to add to the information extant on the angular distribution of light, and to present evidence that at great depths a limiting angular distribution pattern of intensity is approached. This pattern is defined as that of characteristic diffuse light. In another paper the author has developed a general law for the diminution of light intensity based on this concept (4).

FIRST MEASUREMENTS

Figure 25 shows light intensities measured in a vertical plane for 3, 6, and 9 meters. Figure 26 shows measurements in a horizontal plane for the same depths. These readings were taken in Trout Lake, Wisconsin in August 1937 with a photocell and amplifier described by the author in an article on the microstratification of inland lakes (5). A cylindrical hood over the apparatus confined the light received to an angular opening of about 15 degrees. The apparatus was suspended by a bifilar suspension at a given zenith angle, and then rotated in a horizontal plane. In Figure 25 the intensity from beneath is made arbitrarily equal to one for all depths. On this scale the intensity from above increases from 40 units at 3 meters to 100 units at 9 meters. The intensity from the direction of the solar beam decreases from 190

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units at 3 meters to 138 units at 9 meters. In Figure 26 the intensity in a horizontal plane in a direction opposite the sun has been made equal to one unit for all depths. Toward the sun, the intensities are about four, three, and two units respectively in order of increasing depth.

![Light Vector Diagram](image)

Figure 25. Light vector diagram in vertical plane including sun. Trout Lake, Wisconsin, August 1937.

The relative increase in light intensity from above as compared with the decrease from the direction of the solar beam is unmistakable. The measurements in the horizontal plane show that the light intensity becomes more symmetrical about a vertical axis as depth increases.

**MEASUREMENTS WITH ROTATING PHOTOCCELL**

It became evident when using the original apparatus that measurements should be taken at close intervals in the vicinity of the maximum intensity. It also seemed advisable to revise the apparatus for rapid
rotation in a vertical plane. As a matter of fact, speed in readings is of the utmost importance since the zenith angle of the sun changes continuously. This angular change is often greater than the change one is attempting to measure. High sensitivity is also of utmost importance.

The new apparatus consisted of a water tight brass cylinder which contained a photocell, amplifying tube, three small dry cells for C bias, and a rotating screen which permitted different amounts of light to enter the photocell. The screen was controlled by an electromagnet. A hood with several diaphragms to eliminate reflected light confined the light received to a 15 degree angle. The cylinder was connected to the control box by means of a 100 meter four wire cable. The control box contained a second stage of amplification, necessary meters, and batteries. The circuit was similar to the one used in micro-stratification work. The cylinder was free to rotate on a horizontal axis and was supported in a frame which hung vertically from a
bifilar suspension. A ratchet mechanism attached to the cylinder caused a rotation of 10° each time a cord was pulled. After the last pull, the cylinder automatically returned to the starting position by action of a spring. The work with this apparatus was done at the Woods Hole Oceanographic Institution.

Figure 27 shows readings taken August 23, 1939 in Woods Hole Harbor at 3 and 5 meters in depth. The 0° vertical section is the vertical plane including the sun; at right angles to this plane is the 90° vertical section. For purposes of comparison the maximum readings are made to coincide. It has been stated that light becomes more diffuse in deep water; the contrast between these two sections suggests a new meaning to the idea of diffuseness in natural waters. The pattern of the 0° vertical section is broader at 5 meters than at 3 meters, while the 90° pattern is just the reverse, being narrower at 5 meters. Probably an equilibrium condition is being approached in
which light intensity tends to become symmetrical about a vertical axis.

Further evidence of this fact is to be found in certain readings of the $0^\circ$ vertical section. The ratio of the $90^\circ$ zenith angle reading, to the $270^\circ$ zenith angle reading, or the horizontal reading toward the sun compared to the horizontal reading away from the sun, becomes closer to unity at greater depths. This ratio is 2.1 at 3 meters and 1.4 at 5 meters. The ratio of the maximum reading to the $0^\circ$ zenith angle also tends to approach unity. The values of this ratio are 3.8, 2.4, and about 1.4 at depths of 3, 5, and 8 meters respectively.

![Diagram of vertical sections](image)

Figure 28. Vertical section light vectors. Taken just beyond Continental Shelf, September 2, 1939.

The second set of readings was taken from the research ship, Atlantis, just beyond the Continental Shelf at $39^\circ 34'\ N.$ latitude and $71^\circ 05'\ W.$ longitude. The water was more transparent and had fewer scattering particles than the Woods Hole Harbor water. The Atlantis did considerable rolling and pitching, but readings were sufficiently definite to confirm the tendencies shown by the first set of readings in Woods Hole Harbor. The apparatus was suspended from a boom over the stern of the vessel. Figure 28 shows $0^\circ$ vertical sections with the maximum reading for each depth set equal to unity. The proportionate $0^\circ$ zenith angle reading and the readings each side the maximum are shown numerically on the figure. The zenith reading becomes relatively greater in deeper water. The readings each side the maxi-
mum also become relatively greater; in other words, the maximum become broader. Under the experimental conditions any attempt to measure accurately the shift in zenith angle of maximum intensity was out of the question, but there was some shift toward the zenith with depth. There is no question that the pattern broadened with depth.

90° VERTICAL SECTIONS

Figure 29. Vertical section light vectors. Taken just beyond Continental Shelf, September 2, 1939.

The 90° vertical sections illustrated in Figure 29 also show the reverse tendency as depth increases. For purposes of comparison, the 30° zenith angle reading is expressed in terms of the maximum. For example, a large 30° reading relative to the maximum would mean greater diffusion in the sense of equality of light from all directions. But as depth increases, or, as the diffusion approaches the maximum amount possible, the light becomes more directional from the zenith. The broader tops of the shallow water curves are probably due to the fact that the refracted rays from the sky have not as yet lost their
predominance. At 30 meters the direct rays from the sky have become relatively insignificant. An elongated oval-like pattern is approached which is evidence of the small amount of scattering in this water. Since the pattern represents approximately the maximum diffusion in deep water, it may be defined as that of characteristic diffuse light. The idea that maximum (or ultimate) diffusion means equality of

![Diagram of vertical sections]

Figure 30. Vertical section light vectors under conditions of evenly clouded sky. Taken ¾ mile SSE of Tarpaulin Cove Light in Vineyard Sound, August 26, 1939.

light intensity in all directions ignores the fact that the light source itself must be in some particular direction.

The readings shown in Figure 30 were taken with a completely clouded and diffuse sky. The sun was entirely obscured and only one vertical section was taken. It was assumed that other vertical sections would be the same. The readings were obtained about ¾ miles S. S. E. of the Tarpaulin Cove Light in Vineyard Sound. It might be expected that these curves should be similar to the 90° vertical section curves of Figure 29 since a clouded diffuse sky and a clear uniform blue sky
should furnish approximately equal light intensities at all angles. However, the water beyond the continental shelf was clearer and subject to less scattering; hence the slower loss in the directional properties of the sky light as contrasted with the more rapid loss in the Sound. That this rapid loss is due to the character of the water and not to the condition of the sky is shown in the 90° vertical section of Figure 27. These readings were taken in bright sunlight but there is a rapid loss of the directional properties of the sky radiation due to the higher turbidity of the water in Woods Hole Harbor. As a matter of fact, there is little evidence of a broad top to the curve even at 3 meters.

Several interesting facts stand out upon a careful examination of Figure 30. There is a regular change in the curves as deeper water is reached; the upper portions become uniformly narrower, the lower portions broader. It seems obvious that there must be a limit to this process; it may be that the limiting pattern is symmetrical not only about a vertical axis but also about a horizontal plane as well. This possibility suggests theoretical investigation.

The fact that the changes are small seems good evidence that the pattern is practically that of characteristic diffuse light. The shape of this pattern probably depends on the relative values of the absorption and scattering coefficients. Possibly a theoretical derivation of such characteristic curves can be worked out.

It seems reasonable that the characteristic pattern will be approached rapidly, or within a short distance of the surface, if total absorption or scattering is large. The shape of the pattern approached should depend on the relative values of the absorption and scattering coefficients.

In Figure 30 and in many other sets of readings taken, it has been found that the reading vertically downward is approximately half the reading taken in a horizontal direction. This seems to be true where readings are symmetrical about a vertical axis as, for example, when readings are taken in deep water. Of course, light intensities directed upward in deep water are often too faint to be reliable. The following approximate and incomplete line of reasoning, however, suggests that there may be some significance to this two to one ratio of intensities. Assume that a light receiver has unit cross section and that it receives light in a horizontal direction from a column of unit cross section extending an infinite distance horizontally from the receiver. Assume also that the total light striking the receiver is the summation of all the amounts scattered toward the receiver, and reduced in accordance with the exponential law. This gives for the horizontal intensity:
The amount scattered from each contributing element of volume is proportional to \( I' \) the total light intensity at the level of the contributing elements and which is constant for this integration, to \( dy \) the thickness of each contributing layer, and to \( f \) a constant of proportionality which is a measure of the scattered light sent toward the receiver. The amount contributed from below yields a similar expression with the single exception that the light intensity at the level of the contributing elements is no longer constant but equals \( I'e^{-kz} \) where \( I' \) remains the light intensity at the level of the receiver. Performing this integration the intensity upward is:

\[
I_u = fI' \int_0^\infty e^{-2kx} dx = fI'/2k.
\]

This is half the horizontal intensity. This treatment assumes that \( f \), the proportionality constant for scattered light, is the same in all directions. This assumption is discussed by the author in the paper on the general diminution law (4).

**DISCUSSION**

Measurements of the angular distribution of light in natural waters show that as light reaches greater depths the directional properties of the refracted sun and sky light become less important. Light intensities in a vertical plane passing through the sun, or in the 0° azimuthal plane, show diminishing intensities toward the sun and a general broadening with depth. Readings taken in the 90° azimuthal plane, or readings taken in a vertical plane when the sky was uniformly clouded, showed a narrowing of the pattern with depth. In both planes the relative intensity toward the zenith increased. In all cases a pattern which is symmetrical about a vertical axis is approached in deep water.

The limiting angular distribution pattern seems to be oval shaped, possibly symmetrical about a horizontal plane as well as about a vertical axis. The exact shape of the pattern is probably a function of the scattering and absorption coefficients. Experiment and theory lead to the belief that a reading taken with the receiver face down should be half the reading in a horizontal direction.

**SUMMARY**

1. The angular distribution of light intensity was studied in Trout Lake, Wisconsin, Woods Hole Harbor, beyond the Continental Shelf, and in Vineyard Sound.
2. Evidence pointed to a limiting pattern in each case. The pattern is defined as that of characteristic diffuse light.

3. The pattern is approximately oval shaped and elongated toward the zenith.

REFERENCES

(1) Johnson, N. G., and Liljequist, G.

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